Precise GNSS & Maps for Autonomous Vehicles

University of Minnesota Roadway Safety Institute
5 December 2018
OUR VISION
At General Motors, we envision a future with zero crashes, zero emissions and zero congestion:

**Zero crashes** to save lives
Each year close to 1.25 million people die in car crashes around the world, 40,000 in the United States alone. More than 2 million people are injured. Human error is a major contributing factor in 94 percent of these crashes.

**Zero emissions** to leave our children a healthier planet
Vehicles release almost 2 billion tons of carbon dioxide into the atmosphere every year.

**Zero congestion** to give our customers back their precious time
In the United States, commuters spend about a week of their lives in traffic each and every year. That’s a week not spent with those we love, doing what we want to do and being where we want to be.
# Autonomous Vehicle Sensor Characteristics

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td><strong>Radar</strong></td>
<td>Relatively Low Cost</td>
<td>Cannot Detect Road Markings</td>
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<tr>
<td></td>
<td>Good Ranging Accuracy</td>
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<tr>
<td><strong>Lidar</strong></td>
<td>Highly Accurate Ranging</td>
<td>Higher Cost</td>
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<td></td>
<td></td>
<td>Less Effective in Featureless Areas</td>
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<tr>
<td></td>
<td></td>
<td>Typically Requires Lidar Map as Reference</td>
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<tr>
<td><strong>Camera</strong></td>
<td>Lower Cost</td>
<td>Less Effective in Featureless Areas</td>
</tr>
<tr>
<td></td>
<td>Good Object Detection</td>
<td>Less Effective in Snow, Darkness</td>
</tr>
<tr>
<td><strong>HD Map</strong></td>
<td>Excellent Accuracy (&lt;10 cm 95%)</td>
<td>Requires Continuous Updates</td>
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<td></td>
<td></td>
<td>High Acquisition Costs</td>
</tr>
<tr>
<td><strong>Motion Sensors</strong> (Gyro, Accel, Wheel Ticks)</td>
<td>Lower Cost</td>
<td>High Drift Rate for MEMS Sensors</td>
</tr>
<tr>
<td><strong>GNSS (GPS, GLONASS, Galileo)</strong></td>
<td>Lower Cost</td>
<td>Poor Performance in Urban Areas, Tunnels</td>
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</table>
Autonomous Vehicle Sensor Integration

**Perception Sensors**
- **Vehicle Reference Frame**

**Sensor Fusion**
- Deeply integrated
- Input quality characterization
- Integrity monitoring
- Reference frame alignment
- Vehicle position state estimation (translation, rotation)

**Vehicle Control**
- Path planning
- Steering and braking

**Absolute Localization Sensors**
- Global Reference Frame (e.g., ITRF-2000, WGS-84)

**Precise Map**
- Road attributes aligned to global reference datum
- Usually surveyed in advance with Lidar/Camera and RTK

**GNSS**
- Tight Coupling with GNSS measurements (code, carrier, Doppler, range residuals, etc.)
- Vehicle attitude (roll, pitch, yaw & rates)

**IMU**
- Road attributes aligned to global reference datum
- Usually surveyed in advance with Lidar/Camera and RTK

**Lidar**
- Long range, short range
- Front, Side, Rear
- Permanent and stationary objects

**Camera**
- Object Data (Lane Markings, Signs, etc.)

**Radar**
- Cartesian Vectors
- Reflected Intensity

**Corrected through PPP/RTK**
- Lat, Lon, Speed, Heading, Elevation
- Quality Metrics
Connectivity Requirements for Precise GPS & Map

GNSS Corrections
- Low rate (< 2 kbps)
- Delivered through satellite L-band or mobile IP
- Clock, orbit, ionosphere, troposphere state corrections
- Required for confident lane identification and sensor redundancy
- Sub-meter (2-sigma) target for autonomous vehicles

Precise Map Updates
- Periodic updates to vehicle database
- Delivered through mobile IP or Wi-Fi
- Lane markings, road attributes, construction areas

Remote Diagnostics
- Autonomous vehicle health and status telemetry
- Valuable for engineering continuous improvement

Over-the-Air Software Updates
- Improve customer experience
- Improve performance and fix bugs

Live Advisor Services
- Navigation routing, emergencies, peace of mind
V2X Communication

Competing radio standards
- Cellular V2X (C-V2X)– Traction in China
- Digital Short Range Communications (DSRC)– Deployed on GM MY2017 Cadillac CTS Sedan, Traction in North America
- Both operate within 5.9 MHz spectrum
- Incompatible standards– has hindered broader automaker adoption

Example Use cases

V2I:
- Electronic Toll Collection
- Media Sharing: Peer-to-peer Infotainment
- Bridge & Parking Space height warning

V2V:
- Autonomous Driving
- Road Platooning
- Driver Behavior Profile Broadcast
- Hard Braking Ahead Warning
- intersection Collision Warning
- Wrong Way Driver Warning
- Curve Speed Warning
- Traffic Jam Ahead Warning
GM Super Cruise

Cadillac CT6 with Super Cruise

• Internal combustion engine
• Industry’s first true hands-free driving technology for the freeway
• Retail Availability: Q4 2017
• Standard on CT6 Platinum, Optional Feature on CT6 Premium
• Becoming available on all Cadillac models, rollout starting 2020. Other GM brands to follow
• 0-85 mph on precisely mapped interstate highways
• Driver attention required!
• Precise map (+/- 10 cm 95%)
• Precise GPS (median 90 cm)

Super Cruise Video
Test Considerations

Precise localization within geodetic reference frame requires:

- Precise map
  - Transition to Crowd Sourcing
- High accuracy GNSS
  - Improved operation in urban areas (opportunity to include camera video in GNSS/IMU filter)
- Improved IMU
  - Low gyro bias drift rate, low angular random walk

Efficient testing:

- Characterize absolute map accuracy using surveyed RTK reference points
- Audit sample of reference points to statistically characterize accuracy
  - Lane Markings
  - Lane merges/splits
  - Road signs
- Super Cruise Lidar/RTK map achieves +/- 10 cm absolute accuracy with 95% confidence
Sample Test Results– Super Cruise GPS Accuracy
10 July 2018
Warren, MI to Port Austin, MI

10July18 To Port Austin OpenSky VCP RTDR (GPSGLO + DR + RTX) vs Trimble EVK (GPSL1L5 + WAAS)

<table>
<thead>
<tr>
<th>OnStar GNSS Module</th>
<th>Reference GNSS Receiver</th>
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</thead>
<tbody>
<tr>
<td>Average Error = 0.39667758</td>
<td>Average Error = 0.89560941</td>
</tr>
<tr>
<td>Stdev Error = 0.2642552</td>
<td>Stdev Error = 0.26566555</td>
</tr>
<tr>
<td>Max Error = 1.7438135</td>
<td>Max Error = 1.8662224</td>
</tr>
<tr>
<td>Min Error = 0.00048212404</td>
<td>Min Error = 0.19279329</td>
</tr>
<tr>
<td>1-Sigma Error = 0.46414757</td>
<td>1-Sigma Error = 1.0362629</td>
</tr>
<tr>
<td>2-Sigma Error = 0.90934876</td>
<td>2-Sigma Error = 1.3118232</td>
</tr>
<tr>
<td>3-Sigma Error = 1.3605791</td>
<td>3-Sigma Error = 1.6259661</td>
</tr>
<tr>
<td>Time plotted (hrs) = 1.4556</td>
<td>Time plotted (hrs) = 1.4556</td>
</tr>
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</table>
Cruise Automation

Chevy Bolt

- Fully Electric (non combustion engine)
- NHTSA Level 4 Autonomous Vehicle
- Test & Development: San Francisco, Detroit
- Ride sharing service
- Lidar, cameras, radar, precise map
- Lower speeds, urban environment

Cruise Automation Video
Advanced Topic: Visual Enhanced Precise Positioning (VEPP)

- Mass Market, Globally Accurate Positioning

- Tight fusion engine between multiple sensors: GNSS/GPS, camera, IMU, wheel speeds, Trimble RTX
  - Vision input is critical for high accuracy in multi-path environment

- Goal of **sub-meter** accuracy anywhere, anytime

- No dependency on HD Map for high accuracy position in ECEF
  - Achieves high accuracy in global coordinates without accessing a Map database

- Can be coupled with HD map fusion to achieve decimeter accuracy in Map frame
  - Performance validated with major HD Map providers
  - Requires lanes and signs – no dependency on richer feature set beyond these

- CPU and memory optimization underway (Dec 2018)
GNSS/GPS Technologies Primer

Multi-path environment creates challenges for GNSS alone solutions

Note: Feature rich environment for Camera!
How does the Camera help?

- Estimate ego-motion by tracking **sufficient static** features across frames
  - 3D Rotation + 3D translation, **no scale**